Possible Single Resonant Production of the Fourth Generation Charged Leptons at γe Colliders

R. Çiftçi[*]

Dept. of Eng. of Physics, Faculty of Eng., Ankara University, 06100 Tandogan, Ankara, Turkey

A. K. Çiftçi[†]

Physics Department, Faculty of Sciences, Ankara University, 06100 Tandogan, Ankara, Turkey

S. Sultansoy[‡]

Physics Section, Faculty of Sciences and Arts, TOBB University of Economics and Technology, Ankara, Turkey[§]

(Dated: September 16, 2009)

Abstract

Single resonant productions of the fourth standard model generation charged lepton via anomalous interactions at γe colliders based on future linear e^+e^- colliders with 500 GeV and 1 TeV center of mass energies are studied. Signatures of $\gamma e \to \ell_4 \to e\gamma$ and $\gamma e \to \ell_4 \to eZ$ anomalous processes followed by the hadronic and leptonic decay of the Z boson and corresponding standard model backgrounds are discussed.

PACS numbers: 12.60.-i, 14.60.Hi, 14.80.-j

Keywords: Anomalous interactions; linear colliders; fourth generation charged leptons.

[*]Electronic address: rena.ciftci@cern.ch

[†]Electronic address: ciftci@science.ankara.edu.tr

[‡]Electronic address: ssultansoy@etu.edu.tr

[§]Also at Institute of Physics, Academy of Sciences, H. Cavid Avenue 33, Baku, Azerbaijan

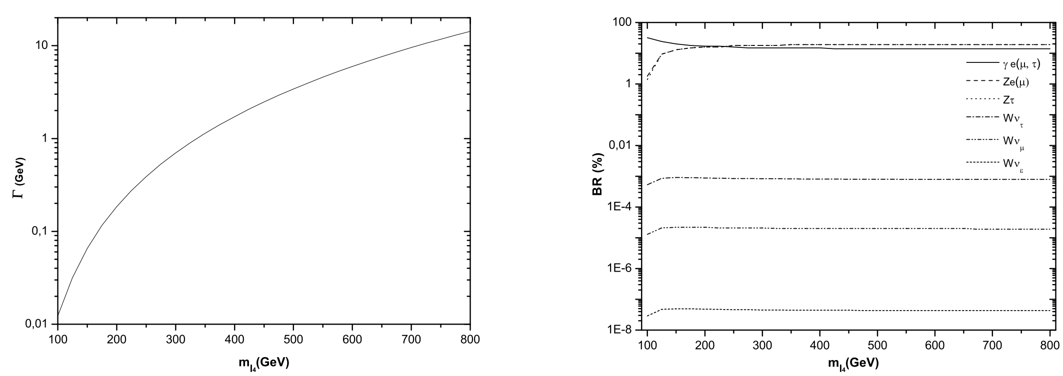
As the LHC run approaches, the interest on fourth standard model (SM) generation is increasing [1]. Actually, existence of the fourth SM family follows from the standard model basics together with mass pattern of the third family fermions [2, 3, 4, 5]. The new quarks (if they exist) will be copiously produced at the LHC [6, 7, 8, 9], whereas the observation of the new leptons is problematic due to rather small production cross section and large background. Obviously, the best place to investigate the new leptons will be the linear e^+e^- colliders with sufficiently high center of mass energy. If the center of mass energy is not enough for the pair production, single production can be considered. However, the single production of new charged lepton within SM seems not to be so promising [10].

Since the fourth family fermions are expected to be heavy, they can serve us as a window for new physics. The Ref. [11] argues that due the large mass of the t quark, its anomalous interactions should be enhanced compared to that of the lighter SM fermions. Obviously, this argumentation is even more valid for fourth SM family fermions.

It is well known that, the linear e^+e^- colliders provide opportunity to construct γe and $\gamma\gamma$ colliders by producing real high energy γ beam through Compton backscattering of laser photons from high energy lepton beam (see [12] and references therein).

In this paper, we consider single anomalous production of the fourth SM family lepton at future γe colliders. The processes $\gamma e \to \ell_4 \to e\gamma$ and $\gamma e \to \ell_4 \to eZ$ $(Z \to \ell^+\ell^-,\ jetjet)$ are studied.

The anomalous interactions, may rise as prescribed in Ref. [11], cause the flavor changing neutral currents (FCNC). The effective Lagrangian for the magnetic type FCNC of the fourth



(a) (b)

FIG. 1: (a) The total decay width of the fourth generation charged lepton and (b) the branching ratios (%) depending on the mass of the charged lepton.

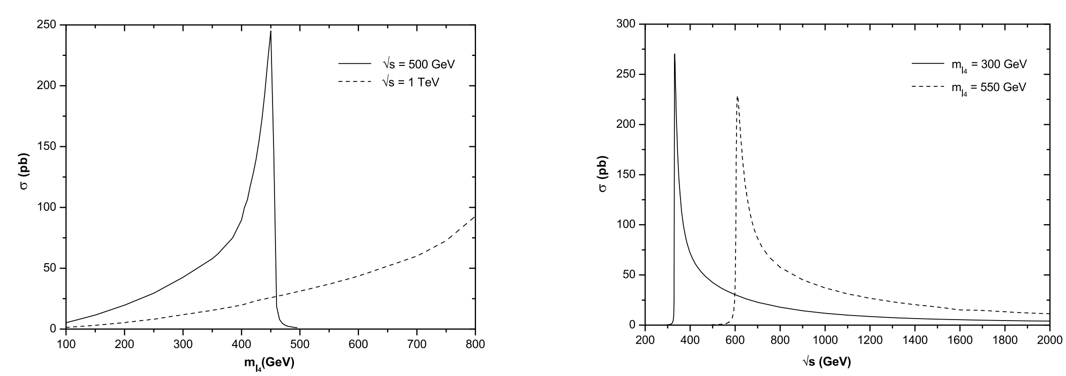
generation charged lepton can be written in a similar manner with [13]

$$L = \left(\frac{\kappa_\gamma^{\ell_i}}{\Lambda}\right) e_\ell g_e \overline{\ell_4} \sigma_{\mu\nu} \ell_i F^{\mu\nu} + \left(\frac{\kappa_Z^{\ell_i}}{2\Lambda}\right) g_Z \overline{\ell_4} \sigma_{\mu\nu} \ell_i Z^{\mu\nu} + h.c. \tag{1}$$

where $i = 1, 2, 3$ correspond to the SM generation numbers; $\kappa^\ell_{\gamma,Z}$ are the anomalous couplings for the neutral currents with a photon and a Z boson, respectively (in this study $\kappa^{\ell_1}_{\gamma,Z} = \kappa^{\ell_2}_{\gamma,Z} = \kappa^{\ell_3}_{\gamma,Z} = \kappa^\ell_{\gamma,Z}$ is taken for simplicity). Λ is the cutoff scale for the new physics and e_ℓ is the charge of leptons; g_e and g_Z are the electroweak coupling constants; $g_e = \sqrt{4\pi\alpha_{em}}$, $g_Z = g_e/cos\theta_W sin\theta_W$, where θ_W is the Weinberg angle. In the above equation, $\sigma_{\mu\nu} = i(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)/2$. $F^{\mu\nu}$ and $Z^{\mu\nu}$ are field strength tensors of the photon and Z boson, respectively.

We have implemented the new interaction vertices into the CompHEP [14] for computations. Naturally, the anomalous interactions will introduce the additional decay channels of the fourth generation charged lepton. While calculating the SM decay contributions, we have used values of the Pontecorvo-Maki-Nakawaga-Sakata (PMNS) mixings given in Ref. [15]. The total decay width of the fourth generation charged lepton and the relative branching ratios are presented in Fig. 1, where $(\kappa_\gamma/\Lambda) = (\kappa_Z/\Lambda) = (\kappa/\Lambda) = 1$ TeV^{-1} is taken. We have used this value at the rest of our calculations. One can rescale our results keeping in mind that anomalous decay widths are proportional to $(\kappa/\Lambda)^2$.

The anomalous single production cross sections of the fourth SM generation charged



(a) (b)

FIG. 2: The production cross sections of the fourth generation charged lepton at γe colliders based on e^+e^- machines (a) as a function of the lepton mass with the fixed center of mass energies of the collider and (b) as a function of center of mass energy of the collider with the fixed masses of the charged lepton.

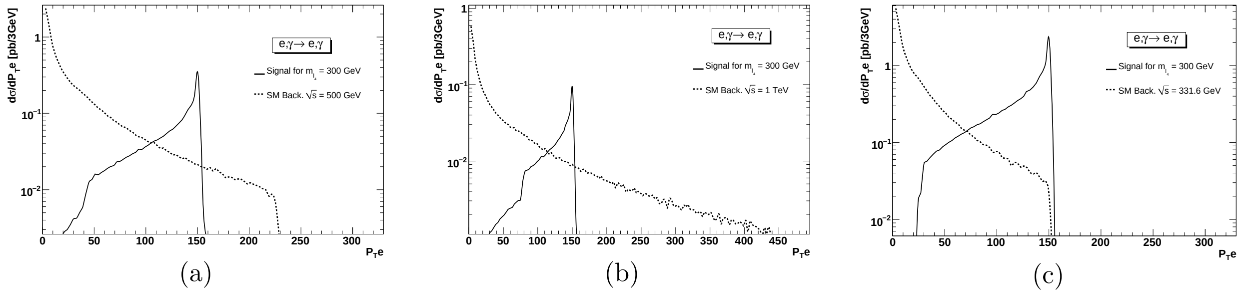


FIG. 3: The P_T distributions for $\gamma e \to \ell_4 \to e\gamma$ signal with 300 GeV lepton mass and corresponding SM background (a) at $\sqrt{s} = 500$ GeV, (b) at $\sqrt{s} = 1$ TeV and (c) at $\sqrt{s} = 331.6$ GeV (at the resonance).

lepton at γe colliders based on future linear e^+e^- colliders with $\sqrt{s} = 500$ GeV and 1 TeV are given in Fig. 2a and 2b, respectively. As seen from Fig. 2a the maximum production cross section of the fourth generation charged lepton at γe colliders based on e^+e^- machines with $\sqrt{s} = 500$ GeV is 245 pb for 450.5 GeV lepton mass. This mass value can be easily understood from kinematics of the γe collider. Indeed, high energy photons can acquire 81% of electron energy at maximum [12]. Therefore, $(\sqrt{s_{\gamma e}})_{max} \cong 0.9\sqrt{s_{e^+e^-}}$. Eventhough the maximum production cross section for $\sqrt{s} = 1$ TeV option is reached at 901 GeV mass value of the lepton, it is plotted in the figure until 800 GeV. The last value is close to the upper limit on heavy fermion masses, which follows from partial-wave unitary at high energies [16].

In principle, adjusting the center of mass energy of γe collider is possible and one can scan $\sqrt{s}$ to find resonance peak. It is possible to decrease the maximum energy of photons by changing the angle of laser with respect to the electron beam. Therefore, one can optimize the center of mass energy of the collider in appropriate manner. As seen from Fig. 2b $\sqrt{s} = 331.6$ GeV and 611 GeV are ideal center of mass energies to produce fourth generation charged lepton with 300 and 550 GeV masses, respectively.

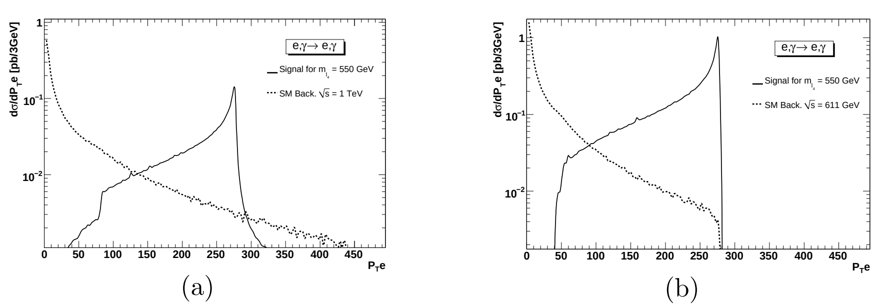


FIG. 4: The P_T distributions for $\gamma e \to \ell_4 \to e\gamma$ signal with 550 GeV lepton mass and corresponding SM background (a) at $\sqrt{s} = 1$ TeV and (b) at $\sqrt{s} = 611$ GeV (at the resonance).

TABLE I: The signal and SM background cross sections for anomalous processes at γe colliders based on e^+e^- machines with $\sqrt{s}$ = 500 GeV (at (κ/Λ) = 1TeV^{-1}). Cut selection criteria are following: Selection 1 is $|\eta_{e,\ell,j}| < 2.5$ and Selection 2 is $|\eta_{e,\ell,j}| < 2.5$, $P_T^e > 100$ GeV and $\Delta R_{jj} > 0.4$.

	Signal cross sections (pb)					
	$\gamma e \to e\gamma$		$\gamma e \to e\ell\ell$		$\gamma e \to ejj$	
m_{ℓ_4} (GeV)	Selection 1	Selection 2	Selection 1	Selection 2	Selection 1	Selection 2
300	6.3	4.8	0.50	0.35	5.0	3.5
350	8.5	7.1	0.72	0.58	7.2	5.9
400	13	12	1.2	1.0	12	10
425	19	17	1.7	1.5	17	15
450	34	31	3.0	2.7	30	27
SM Backg. (pb)	32	2.6	2.5	0.26	3.5	0.61

Below $\gamma e \to \ell_4 \to e\gamma$ and $\gamma e \to \ell_4 \to eZ$ signal processes followed by the hadronic and leptonic decay of the Z boson ($j = u, d, s, c, b$ and $\ell = e, \mu$) as well as their SM backgrounds are considered. Some kinematic cuts have been applied in order to suppress the SM background. First, a generic $|\eta_{e,\ell,j}| < 2.5$ cut is chosen, where η denotes the pseudorapidity. After the η cut we have plotted the P_T distributions of the electron for $\gamma e \to \ell_4 \to e\gamma$ and corresponding background processes for 300 GeV lepton mass in Figs. 3 and for 550 GeV lepton mass in Figs. 4 to determine the optimum P_T cut value. It is seen that $P_T^e > 100$ GeV removes the most of the background while preserves the most of the signal events. Similar statement is valid for the remaining processes (we do not give corresponding figures to save the space). The computed signal and background cross sections for processes under consideration are presented in Tables I and II for $\sqrt{s} = 500$ GeV and 1 TeV options, respectively. Results of the similar analysis for ideal center of mass energy are presented in Table III. The advantage of the tuning of $\sqrt{s}$ at γe colliders is seen from the comparison of Table III with Tables I and II.

It is clear that with $\kappa/\Lambda = 1$ TeV^{-1} one can discover the fourth generation charged lepton until the mass within kinematical limit of the collider. In order to obtain achievable values of the anomalous coupling strength, we require statistical significance (SS) greater than 3

TABLE II: The same as Table I but for $\sqrt{s} = 1$ TeV.

	Signal cross sections (pb)					
	$\gamma e \rightarrow e\gamma$		$\gamma e \rightarrow e\ell\ell$		$\gamma e \rightarrow ejj$	
m_{ℓ_4} (GeV)	Selection 1	Selection 2	Selection 1	Selection 2	Selection 1	Selection 2
300	1.7	1.3	0.12	0.090	1.2	0.94
400	2.8	2.6	0.23	0.21	2.3	2.2
500	4.3	4.0	0.37	0.36	3.9	3.6
550	5.1	4.8	0.45	0.44	4.6	4.4
600	6.0	5.7	0.54	0.53	5.5	5.3
700	8.3	8.1	0.77	0.76	8.0	7.6
800	13	13	1.2	1.2	12	12
SM Backg. (pb)	9.1	1.6	0.64	0.34	0.93	0.54

and at least 5 events per working year (10^7 s) as observation criteria. SS values are evaluated from [17]

$$SS = \sqrt{2 \times L_{\gamma e}[(\sigma_s + \sigma_b) ln(1 + \frac{\sigma_s}{\sigma_b}) - \sigma_s]} \tag{2}$$

where $L_{\gamma e}$ is the integrated luminosity of the γe collider, which is taken as 65% of 100 fb^{-1} for $\sqrt{s_{ee}} = 500$ GeV and 65% of 300 fb^{-1} for $\sqrt{s_{ee}} = 1$ TeV.

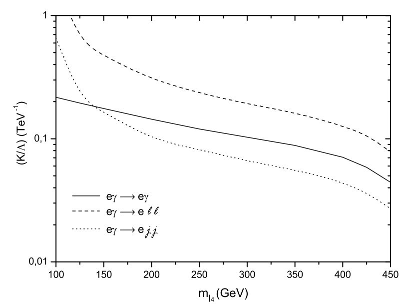
Achievable values of the anomalous coupling strengths are shown in Figs. 5a and 5b for 500 GeV and 1 TeV center of mass energies, respectively, as a function of the lepton mass. One can see that values as low as 0.027 TeV^{-1} (0.023 TeV^{-1}) are reachable for κ/Λ with

TABLE III: The same as Table I but for ideal center of mass energies for $m_{\ell_4} = 300$ and 550 GeV.

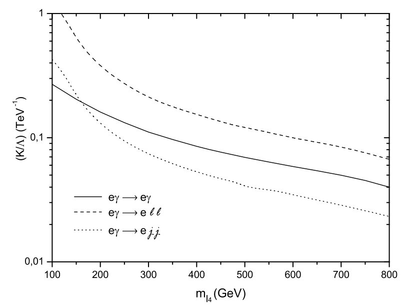
		Signal cross sections (pb)					
		$\gamma e \rightarrow e\gamma$		$\gamma e \rightarrow e\ell\ell$		$\gamma e \rightarrow ejj$	
m_{ℓ_4} (GeV)	$\sqrt{s_{ee}}$ (GeV)	Selection 1	Selection 2	Selection 1	Selection 2	Selection 1	Selection 2
300	331.6	40	30	3.2	2.2	33	22
Backg. (pb)		66	2.4	5.5	0.14	3.3	0.37
550	611	32	30	2.9	2.8	29	28
Backg. (pb)		22	2.4	1.7	0.30	2.6	0.61

$\gamma e \to ejj$ process at $\sqrt{s} = 500$ GeV with integrated luminosity of 100 fb^{-1} (at $\sqrt{s} = 1$ TeV with $L_{int} = 300$ fb^{-1}). Moreover, it is possible to differ κ_γ/Λ from κ_Z/Λ by using informations coming from $\gamma e \to e\gamma$ or $\gamma e \to eZ$ processes, because corresponding cross sections are scaled as $(\kappa_\gamma/\Lambda)^2\kappa_\gamma^2/(\kappa_\gamma^2 + \kappa_Z^2)$ and $(\kappa_\gamma/\Lambda)^2\kappa_Z^2/(\kappa_\gamma^2 + \kappa_Z^2)$, respectively. The reachable values of anomalous photon and Z boson couplings are shown in Fig. 5c.

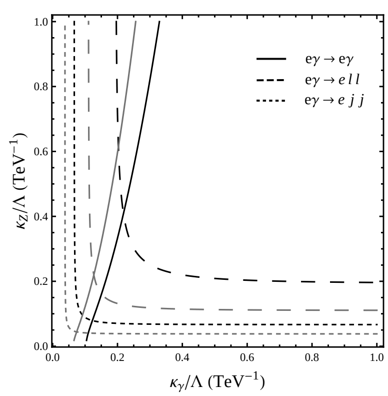
The lowest necessary luminosities of e^+e^- machines to observe anomalous processes are plotted as a function of the lepton mass in Figs. 6a and 6b for $\sqrt{s} = 500$ GeV and 1 TeV options with $(\kappa/\Lambda) = 1$ TeV^{-1}, respectively. It is seen that the single resonant production of the new charged lepton at γe colliders based on e^+e^- machines with $\sqrt{s} = 500$ GeV will be observed almost in a working day for $m_{l_4} \geq 140$ GeV with $\gamma e \to ejj$ process. The



(a)



(b)



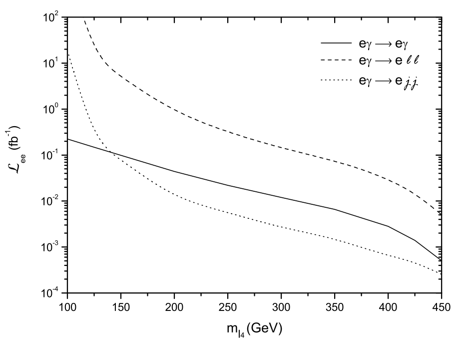
(c)

FIG. 5: The achievable values of the anomalous coupling strength at γe colliders based on e^+e^- machines with (a) $\sqrt{s} = 500$ GeV and (b) $\sqrt{s} = 1$ TeV as a function of the charged lepton mass; (c) the reachable values of anomalous photon and Z couplings for $m_{\ell_4} = 300$ GeV at $\sqrt{s} = 500$ GeV with $L_{int} = 100$ fb^{-1} (black lines) and for $m_{\ell_4} = 550$ GeV at $\sqrt{s} = 1$ TeV with $L_{int} = 300$ fb^{-1} (grey lines). Cut selection 1 is used.

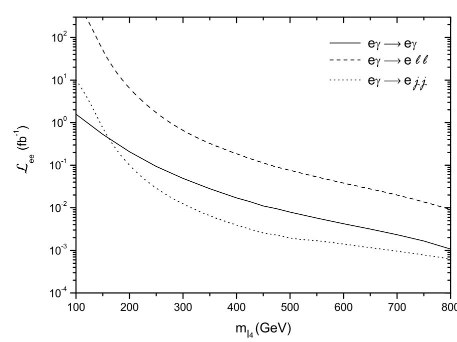
TABLE IV: Improvements with cut selection 2 for ideal $\sqrt{s}$.

	$m_{\ell_4} = 300$ GeV at $\sqrt{s} = 331$ GeV		$m_{\ell_4} = 550$ GeV at $\sqrt{s} = 611$ GeV	
	Selection 1	Selection 2	Selection 1	Selection 2
$\gamma e \to \ell_4 \to e\gamma$	0.049	0.025	0.032	0.019
$\gamma e \to \ell_4 \to e\ell\ell$	0.092	0.044	0.055	0.037
$\gamma e \to \ell_4 \to ejj$	0.026	0.018	0.019	0.014

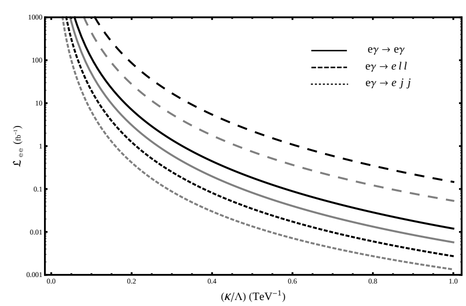
$e\gamma \to e\gamma$ process becomes more advantageous at lepton masses smaller than 140 GeV (Fig. 6a). A similar situation exists for the collider with $\sqrt{s} = 1$ TeV (Fig. 6b). The Fig. 6c presents the lowest necessary luminosities as a function of the observation limit for the anomalous coupling strength for various cases. One can see that with $\sqrt{s} = 1$ TeV and 300 fb^{-1} integrated luminosity κ/Λ values down to 0.038 TeV^{-1} for 550 GeV lepton mass



(a)



(b)



(c)

FIG. 6: The lowest necessary luminosity values of e^+e^- machines to observe anomalous processes at γe colliders (a) with $\sqrt{s} = 500$ GeV and (b) with $\sqrt{s} = 1$ TeV as a function of the charged lepton mass; (c) as a function of anomalous coupling strength for $m_{\ell_4} = 300$ GeV at $\sqrt{s} = 500$ GeV (black lines) and for $m_{\ell_4} = 550$ GeV at $\sqrt{s} = 1$ TeV (grey lines). Cut selection 1 is used.

will be reached. Similarly, the κ/Λ values down to 0.066 TeV^{-1} for $m_{l_4} = 300$ GeV can be observed with $\sqrt{s} = 500$ GeV and 100 fb^{-1} integrated luminosity. The cut selection 2 causes improvements on achievable values of anomalous couplings. Table IV shows corresponding improvements in the case of ideal $\sqrt{s}$ for $m_{l_4} = 300$ and 550 GeV.

In conclusion, γe colliders will provide unique opportunity to search for anomalous couplings of the fourth SM family charged lepton.

Acknowledgments

This work was supported by the Turkish Atomic Energy Authority (TAEA) and DPT with grant No. DPT2006K-120470.

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